

A Survey of $z > 5.7$ Quasars in the Sloan Digital Sky Survey IV: Discovery of Seven Additional Quasars^{1,2}

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ABSTRACT

We present the discovery of seven quasars at $z > 5.7$, selected from $\sim 2000 \text{ deg}^2$ of multicolor imaging data of the Sloan Digital Sky Survey (SDSS). The new quasars have redshifts z from 5.79 to 6.13. Five are selected as part of a complete flux-limited sample in the SDSS Northern Galactic Cap; two have larger photometric errors and are not part of the complete sample. One of the new quasars, SDSS J1335+3533 ($z = 5.93$), exhibits no emission lines; the $3\text{-}\sigma$ limit on the rest-frame equivalent width of $\text{Ly}\alpha + \text{NV}$ line is 5 \AA . It is the highest redshift lineless quasar known, and could be a gravitational lensed galaxy, a BL Lac object or a new type of quasar. Two new $z > 6$ quasars, SDSS 1250+3130 ($z = 6.13$) and SDSS J1137+3549 ($z = 6.01$), show deep Gunn-Peterson absorption gaps in $\text{Ly}\alpha$. These gaps are narrower than the complete Gunn-Peterson absorption troughs observed among quasars at $z > 6.2$ and do not have complete $\text{Ly}\beta$ absorption.

Subject headings: quasars: general; quasars: emission line; quasars: absorption lines

1. Introduction

This paper is the fourth in a series presenting i -dropout $z \gtrsim 5.7$ quasars selected from the multicolor imaging data of the Sloan Digital Sky Survey (SDSS; York et al. 2000, Stoughton et al. 2002). In Fan et al. (2000) and in the first three papers of this series (Fan et al. 2001b, Paper I; Fan et al. 2003, Paper II; Fan et al. 2004, Paper III), we presented the discovery of twelve luminous quasars at $z = 5.74 - 6.42$, selected from $\sim 4600 \text{ deg}^2$ of SDSS imaging in the Northern Galactic Cap. In this paper, we describe the discovery of seven new quasars at $z = 5.79 - 6.13$, selected from $\sim 2000 \text{ deg}^2$ of new SDSS imaging data. The scientific objectives, photometric data reduction, candidate selection and additional photometric and spectroscopic observation procedures are described in detail in Paper I and will not be repeated here. We present the photometric observations of the i -dropout candidates in the new area in §2. The spectroscopic observations and the photometric and spectroscopic properties of the newly-discovered quasars are described in §3. SDSS J133550.81+353315.8¹⁷ ($z = 5.93$, SDSS J1335+3533 for brevity) is a quasar without detectable emission lines; we discuss the properties of this unusual object in §4.

Following the previous papers in this series, we use two cosmologies to present our results: (1) $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0$ and $\Omega_M = 1$ (Ω -model); (2) $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$ and $\Omega_M = 0.27$ (Λ -model, Spergel et al. 2003).

¹⁷The IAU naming convention for SDSS sources is SDSS JHHMMSS.SS±DDMMSS.S, and the positions are expressed in J2000.0 coordinates. The astrometry is accurate to better than $0.1''$ in each coordinate.

2. Candidate Selection and Identification

The Sloan Digital Sky Survey is using a dedicated 2.5m telescope (Gunn et al. 2005) and a large format CCD camera (Gunn et al. 1998) at the Apache Point Observatory in New Mexico to obtain images in five broad bands (u , g , r , i and z , centered at 3551, 4686, 6166, 7480 and 8932 Å, respectively; Fukugita et al. 1996, Stoughton et al. 2002) of high Galactic latitude sky in the Northern Galactic Cap. About 7400 deg² of sky have been imaged at the time of this writing (August 2005). The imaging data are processed with a series of pipelines (Lupton et al. 2001, Pier et al. 2003), resulting in astrometric calibration errors of $< 0.1''$ rms per coordinate, and photometric calibration to better than 0.03 mag (Hogg et al. 2001, Smith et al. 2002, Ivezić et al. 2004, Tucker et al. 2005). These data have been made publicly available in a series of data releases (EDR: Stoughton et al. 2002; DR1 – DR4: Abazajian et al. 2003, 2004, 2005, Adelman-McCarthy et al. 2005).

Quasars at redshifts larger than 5.7 have $i - z > 2.2$ in the SDSS filter system, and become i -dropout objects with weak or no detection in all but the reddest (z) band. In Papers I - III, we presented results from a survey of i -dropout quasar candidates selected from ~ 4600 deg² of high Galactic latitude sky in the SDSS Main Survey area, observed in the Springs of 2000 - 2003. In the Springs of 2004 and 2005, we continued the search in 92 new SDSS imaging runs. These imaging data were taken between May 2003 (Run 3926) and April 2005 (Run 5237), and cover ~ 2400 deg² of the sky. We applied the same color selection criteria as in Paper II (see Figures 1 and 2 in Paper II) to the new SDSS imaging data to select $z > 5.7$ quasar candidates. A total of ~ 230 i -dropout candidates that satisfy the color selection criteria (with z -band photometric error $\sigma(z) < 0.10$) were selected in the main survey area. These candidates were selected as part of a flux-limited complete sample (Paper III). We have also selected a number of fainter candidates with larger z -band photometric error $\sigma(z) = 0.10 - 0.12$, although they are not part of the complete sample.

The photometric and spectroscopic observations were carried out over a number of nights between January 2004 and June 2005. A total of 198 candidates (85% of those selected) from the complete sample were observed; thus the effective area of this sample is ~ 2000 deg². In addition, data on about thirty fainter candidates with $\sigma(z) = 0.10 - 0.12$ were also acquired. We first obtained independent z photometry to eliminate false detections due to cosmic rays and to improve the $i - z$ color measurement, using the Seaver Prototype Imaging Camera (SPICAM) on the ARC 3.5m telescope at the Apache Point Observatory. Unfortunately, poor weather limited the number of objects we were able to observe in the z band.

Additional J -band photometry allows separation of $z \sim 6$ quasars from L/T dwarfs, which have similar $i - z$ colors but much redder $z - J$ colors (e.g. Paper I). J -band observations were carried out using a number of IR imagers: (1) the 256×256 NICMOS imager on Steward Observatory's 2.3m Bok Telescope at Kitt Peak; (2) GRIM II (the near infrared GRISM spectrometer and IMager), on the ARC 3.5m, which we used through December 2004; (3) NIC-FPS (the Near-Infrared Camera/Fabry-Perot Spectrometer), also on the ARC 3.5m, which

replaced GRIM II in December 2004; and (4) PANIC (Persson’s Auxiliary Nasmyth Infrared Camera, Martini et al. 2004) on the 6.5m Baade Telescope at Las Campanas Observatory.

Spectroscopic observations were carried out over a number of observing runs between January 2004 and June 2005 using: (1) the Red-Channel Spectrograph on the MMT 6.5-m telescope on Mt. Hopkins, (2) the Multi-Aperture Red Spectrograph (MARS) on the 4-m telescope on Kitt Peak, and (3) the Echellette Imaging Spectrograph (ESI, Epps & Miller 1998) on the Keck II telescope on Mauna Kea, Hawaii.

3. Discovery of Seven New Quasars at $z > 5.7$

Among the 198 i -dropout candidates with $\sigma(z) < 0.10$ that we have observed, 52 are false z -band only detections which are most likely cosmic rays; 129 are M or L dwarfs (mostly classified photometrically based on their red $z - J$ colors); and 12 are likely T dwarfs (Chiu et al. 2005). Several objects still lack proper infrared spectroscopy, so the T dwarf classification is still preliminary. We have not yet obtained J -band photometry for the remaining candidates. Therefore the quasars reported in this paper do not form a complete sample. Among the faint ($\sigma(z) > 0.10$) candidates that are not identified as quasars, roughly half are likely cosmic rays and half are late-type stars, although the larger photometric error does not allow accurate typing.

Five of the i -dropout candidates with $\sigma(z) < 0.10$ and two faint candidates with $0.10 < \sigma(z) < 0.12$ are identified as quasars at $z = 5.79 - 6.13$. The finding charts of the seven new quasars are presented in Figure 1. Their spectra are flux-calibrated to match the observed z -band photometry and are shown in Figure 2. Table 1 presents the photometric properties of the new quasars, and Table 2 presents the measurements of their continuum properties. Following Papers I-III, the quantity AB_{1280} is defined as the AB magnitude of the continuum at rest-frame 1280 Å, after correcting for interstellar extinction using the map of Schlegel, Finkbeiner & Davis (1998). We extrapolate the continuum to rest-frame 1450 Å, assuming a continuum shape $f_\nu \propto \nu^{-0.5}$, to calculate AB_{1450} . None of the seven quasars is detected in the FIRST (Becker, White & Helfand 1995) or NVSS (Condon *et al.* 1998) radio surveys. FIRST survey has typical 5- σ flux limit of $\sim 1\text{mJy}$ at 20cm. Assuming a power law continuum of $f_\nu \propto \nu^{-0.5}$ in both radio and UV wavelengths, we find that quasars in this paper have radio loudness parameter $R = F_{5\text{GHz}}/F_{4400}$ smaller than 10, the usual division between radio-loud and radio-quiet objects (e.g. White et al. 2000). We have checked the publicly available archival X-ray coverage of these seven quasars, focusing on observations made by sensitive X-ray imaging detectors. SDSS J0927+2001 and SDSS J1250+3130 lie within pointed X-ray observations made by the *Einstein* IPC (1.7 ks) and *ROSAT* PSPC (0.7 ks), respectively, but no X-ray detections were obtained. The relatively short exposures and significant off-axis angles of these two quasars do not allow physically tight constraints to be placed upon their X-ray-to-optical flux ratios (see Strateva et al. 2005). The other five quasars only have imaging X-ray coverage in the *ROSAT* All-Sky Survey, and no detections were obtained, indicating 3- σ upper limits of X-ray flux of $\sim 3.1 - 5.7 \times 10^{-13} \text{ erg cm}^{-2}\text{s}^{-1}$ in

the 0.1 – 2.4 keV band. Results from a recent *Chandra* observation of SDSS J0840+5624 will be reported in O. Shemmer et al., in preparation. The discovery of these seven new quasars brings the total number of $z > 5.7$ quasars from the SDSS to nineteen.

3.1. Notes on Individual Objects

SDSS J081827.40+172251.8 ($z = 6.00 \pm 0.02$). This quasar was discovered using the Keck II telescope on April 12, 2005. Figure 2 shows a spectrum with 20 minute exposure time using Keck/ESI, smoothed to a resolution of 1800. SDSS J0818+1722 has very weak emission lines: the rest-frame equivalent width of $\text{Ly}\alpha + \text{NV}$ is $\sim 10 \text{ \AA}$, compared to an average of $\sim 75 \text{ \AA}$ for high-redshift quasars (Schneider et al. 1991, Fan et al. 2001a, Paper III). The current spectrum has moderate S/N; $\text{Ly}\alpha + \text{NV}$ is the only detected line. The redshift is determined from the fit to the $\text{Ly}\alpha + \text{NV}$ complex. The uncertainty in this redshift comes from two sources. The first is due to absorption in the blue end of the line due to absorption from the $\text{Ly}\alpha$ forest. The second is the offset in the redshift determined from $\text{Ly}\alpha$ and from high ionization lines such as CIV on one hand, and that from low ionization lines such as MgII on the other. Richards et al. (2002b) use a large sample of SDSS quasars to show that CIV is blueshifted from MgII by $824 \pm 511 \text{ km s}^{-1}$, corresponding to an uncertainty of ~ 0.02 at $z \sim 6$. Following Papers I-III, we adopt an error bar of 0.02 in the quasar redshift to reflect these uncertainties.

There is also a strong absorption line at $\sim 8870 \text{ \AA}$ which is resolved into a doublet in the full resolution spectrum. We tentatively identify this feature as the $\text{CIV}\lambda\lambda 1548, 1551$ doublet at a redshift of 4.726.

SDSS J084035.09+562419.9 ($z = 5.85 \pm 0.02$). This object was discovered on January 13, 2004 using the MMT. Figure 2 shows a spectrum with 60 minute exposure time using the MMT Red Channel Spectrograph. The signal-to-noise ratio (S/N) of the spectrum is relatively low. The redshift is estimated by the best-fit $\text{Ly}\alpha + \text{NV}$ emission.

SDSS J092721.82+200123.7 ($z = 5.79 \pm 0.02$). This quasar was discovered on May 6, 2005 using the Kitt Peak 4-m telescope. Figure 2 shows a spectrum with 220 minute exposure time with the MARS spectrograph on the Kitt Peak 4-meter. The redshift is estimated by the best-fit $\text{Ly}\alpha + \text{NV}$ emission.

SDSS J113717.73+354956.9 ($z = 6.01 \pm 0.02$). This quasar was discovered on April 27, 2004 using the MMT. Figure 2 shows a 40 minute Keck/ESI spectrum taken on January 6, 2005. The spectrum shows clear detections of $\text{Ly}\alpha + \text{NV}$, OI and SiIV emission. We adopt the average of the best-fit values of these lines as the quasar redshift. A strong and marginally resolved absorption feature is detected at 9180 \AA ; we are not able to unambiguously identify this feature.

The absorption spectrum shows a dark absorption gap in $\text{Ly}\alpha$ transition immediately blueward of the emission line, where no flux is detected. Following Becker et al. (2001), Fan et al.

(2002) and White et al. (2003), we define the transmitted flux ratio as:

$$\mathcal{T}(z_{abs}) \equiv \langle f_{\nu}^{obs} / f_{\nu}^{con} \rangle, \quad (1)$$

where f_{ν}^{con} is the continuum level extrapolated from the red side of the Ly α emission line. We find an average transmitted flux $\mathcal{T} = -0.005 \pm 0.004$ for z_{abs} between 5.83 and 5.90. The effective Ly α optical depth in this dark gap is $\tau_{eff} > 5.5$, comparable to the limits measured in the complete Gunn-Peterson (1965) troughs detected in quasars at $z > 6.1$ (Becker et al. 2001, Fan et al. 2002, White et al. 2003, Paper III, see also Songaila 2004). The redshift extent of this dark gap is considerably narrower than those seen in quasars at $z > 6.1$. Furthermore, flux is clearly detected in the Ly β transition over the same redshift range, with an average transmitted flux of $\mathcal{T}_{\beta} = 0.013 \pm 0.003$, indicating that IGM is still highly ionized in this region, although the mean optical depth has increased substantially from lower redshift. In a subsequent paper (X. Fan, et al. in preparation), we present a full analysis of the Gunn-Peterson absorption in the spectra of this and the other 18 $z > 5.7$ SDSS quasars.

SDSS J125051.93+313021.9 ($z = 6.13 \pm 0.02$). This quasar was discovered on April 24, 2004 using the MMT. We did not carry out J -band photometry; the red $i - z$ color and lack of detection ($J > 16.5$) in 2MASS (Skrutskie et al. 1997) suggested that it was likely to be a high-redshift quasar. Figure 2 shows a 60 minute Keck/ESI spectrum taken on January 6, 2005. The spectrum shows clear detections of Ly α +NV, Ly β +OVI, OI and SiIV emission lines. We adopt the average of the best-fit values of these lines as the quasar redshift. It is the highest redshift object presented in this paper, and the fifth most distant quasar yet discovered. On the blue wing of the OI emission line, a MgII doublet at $z_{abs} = 2.29$ is clearly detected, with a total rest-frame equivalent width of 4.5 Å.

In the absorption spectrum of this quasar, we detect a deep Gunn-Peterson absorption gap at $5.69 < z_{abs} < 5.95$ in Ly α transition. The average transmitted flux, $\mathcal{T} = 0.005 \pm 0.003$, indicates a lower limit of the Gunn-Peterson optical depth $\tau_{eff} > 5.3$. Similar to the case of J1137 + 3549, residual flux is clearly detected over the same redshift range in the Ly β transition, with a transmitted flux of $\mathcal{T}_{\beta} = 0.008 \pm 0.002$.

SDSS J133550.81+353315.8 ($z = 5.93 \pm 0.04$). This quasar was discovered on June 13, 2005 using the MMT. Figure 2 shows a 120 minute MMT/Red Channel spectrum. This object has a z -band photometric error $\sigma(z) = 0.11$, therefore it is not part of the complete flux-limited sample of $z \sim 6$ quasars. SDSS J1335+3533 is the most unusual object presented in this paper: it does not have a detectable Ly α +NV emission line. We discuss its properties and possible interpretations in §4.

SDSS J143611.74+500706.9 ($z = 5.83 \pm 0.02$). This object was discovered on April 28, 2004, using the Kitt Peak 4-m Telescope. Figure 2 shows a spectrum with 60 minute exposure time using the MMT/Red Channel Spectrograph. This object has a z -band photometric error $\sigma(z) = 0.12$, and therefore will not be part of the complete flux-limited sample of $z \sim 6$ quasars. The redshift is estimated by the best-fit Ly α +NV line.

4. SDSS J1335+3533, a Lineless Quasar at $z = 5.93$

Figure 3 shows the MMT spectrum of SDSS J1335+3533. This object is clearly at high redshift: it exhibits a sharp Ly α break at $\lambda < 8410 \text{ \AA}$, and a sharp Ly β break at $\lambda < 7130 \text{ \AA}$, indicating a redshift $z > 5.92$. However, no strong Ly α emission line is detected. Although there is a hint of excess flux at the edge of the Ly α break, the spectrum is consistent with a pure power-law continuum. Fitting a power-law plus emission line model to the spectral region redward of the Ly α break, we find the $3\text{-}\sigma$ limit on the rest-frame equivalent width of Ly α +NV line to be 5 \AA . Most high-redshift quasars are characterized by the presence of strong Ly α and NV emission lines, and the rest-frame equivalent width of Ly α +NV is $70 \pm 15 \text{ \AA}$ for $z \sim 4$ quasars (e.g. Schneider, Schmidt & Gunn 1991, Vanden Berk et al. 2001, Fan et al. 2001a, 2004). Figure 3 also displays the composite spectrum of 16 non-BAL quasars at $z > 5.7$ (excluding SDSS J1335+3533), constructed following the procedure described in Paper III. The lack of Ly α is striking. The current observations do not have sufficient S/N to place strong constraints on the presence of OI and SiIV lines; another strong emission line, CIV, is now beyond $1\mu\text{m}$ and will require new infrared spectroscopy. We base our estimate of the redshift of SDSS J1335+3533 on the size of the proximity effect zone in the Ly α forest close to the Ly α emission line. Details of calculating the size of proximity zone around luminous quasars at $z \sim 6$ are described in a subsequent paper (X. Fan et al. in preparation). Briefly, in regions of the IGM close to the quasar, transmitted flux is enhanced due to increased ionizing flux from the quasar itself. The transmitted flux declines to that in the average IGM at large distance; at $z > 5.7$, $\mathcal{T} < 0.05$. Fluxes in the 16 other $z > 5.7$ non-BAL quasars from the SDSS drop to 20% of the continuum level at a redshift $\Delta z = 0.11 \pm 0.04$ blueward of the Ly α emission line. This value is a function of luminosity and redshift. SDSS J1335+3533 is close to the median redshift and luminosity of our sample. Including these effects does not change our redshift estimate. For this quasar, the transmitted flux falls to 20% of the extrapolation of the long-wavelength flux at $z_{abs} = 5.82$, implying that the true redshift of the quasar is $z = 5.93 \pm 0.04$. We obtain a similar redshift using the onset of the Ly β forest in the spectrum. Note that this redshift determination depends somewhat on the assumed size of the HII region around SDSS J1335+3533.

Lineless quasars are very rare at high redshift. This is unlikely to be a selection effect. The SDSS color selection of high-redshift quasars is mostly based on the presence of a strong Lyman break. It does not strongly select against quasars with small Ly α emission line equivalent widths (Fan et al. 1999, Richards et al. 2002a). The first lineless quasar found at high redshift was SDSS J1532–0030 ($z = 4.62$, Fan et al. 1999); its spectrum is very similar to that of SDSS J1335+3533. Since then, the SDSS has so far discovered about a dozen quasars at $3 < z < 5$ with rest-frame Ly α equivalent width smaller than 5 \AA (e.g., Anderson et al. 2001; Collinge et al. 2005). They appear to form a distinct class of high-redshift *lineless* quasars. SDSS J1335+3533 represents the most distant member of this class of objects.

The nature of these lineless quasars remains a mystery. They could be ultra-luminous or lensed galaxies, high-redshift BL Lac objects, or a new class of quasar with very weak or absent

broad emission lines. The absolute AB magnitude of SDSS J1335+3533 at 1450 Å (rest-frame) is $M_{1450} = -26.81$ (Λ-model). Thus, although the S/N of our optical spectrum is probably not sufficient to rule out the presence of stellar absorption lines, this object is much too luminous to be an ordinary galaxy unless it is strongly lensed. There is no indication that SDSS J1335+3533 is extended beyond the point spread function of the 1.3'' FWHM SDSS image; this is not yet a strong constraint on the lensing hypothesis.

BL Lac objects, by definition, show no or very weak emission lines. They are also characterized by strong radio and X-ray emission, optical variability, and strong and variable optical polarization due to synchrotron radiation from the relativistic jet (e.g. Urry & Padovani 1995). The highest redshift BL Lac in the literature is at $z < 2$ (Laurent-Muehleisen et al. 1999). SDSS J1335+3533 is not detected in the FIRST radio survey; the 4σ upper limit of 0.8 mJy/beam at this position, including CLEAN bias (White et al. 1997). This implies a radio-to-optical spectral index in the observed frame of $\alpha_{ro} < 0.26$ (4σ). Classical radio-selected BL Lacs have $\alpha_{ro} > 0.3$ (Stocke et al. 1990), while X-ray selected BL Lacs can have α_{ro} as small as ~ 0.1 (Laurent-Muehleisen et al. 1999). Collinge et al. (2005) present a sample of 386 BL Lac candidates identified from the SDSS by their lack of emission lines. Most of them are at low redshift ($z < 1$), and only $\sim 3\%$ of these optically-selected candidates have $\alpha_{ro} < 0.2$. SDSS J1335+3533 is also not detected on the ROSAT full-sky pixel images (Voges et al. 1999), implying a 3σ upper limit of X-ray flux of $\sim 3.7 \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$ in the 0.1 – 2.4 keV band, and an optical-to-X-ray index in the observed frame $\alpha_{ox} > 1.1$ at 3σ . This limit does not yet place strong constraints on the BL Lac hypothesis, as it is in the middle of α_{ox} distribution for X-ray selected BL Lacs (Stocke et al. 1990, Sambruna et al. 1996).

The current observations cannot yet place strong constraints on the nature of SDSS J1335+3533: whether it is a lensed galaxy, a very high redshift BL Lac, or a new type of quasar with no or a very weak emission line region. Further observations, including high-resolution imaging to test the lensing hypothesis, optical monitoring for variability, deep radio and X-ray observations (e.g. Schneider et al. 2003), and optical polarimetric measurements to test the BL Lac hypothesis, are needed. Spitzer observations of such objects in the mid-infrared will probe the presence of hot dust in the vicinity of the object, differentiating the hypotheses that the source is AGN-powered, star-formation powered, or beamed (A. M. Diamond-Stanic, et al. in preparation). Stalin & Srianand (2005) suggest that such objects could be explained by microlensing of the continuum source that only boosts the continuum; if this were the case, long-term monitoring would show a decreasing continuum and a detectable Ly α emission line after the lensing event passes.

5. Future Observations

Combining the seven new quasars presented in this paper with those reported in Papers I-III, we have a sample of 19 quasars at $z > 5.7$. Among them, fourteen are selected using a

uniform set of color selection criteria from an effective area of $\sim 6600 \text{ deg}^2$, forming a flux-limited sample. Because the spectroscopic observations of *i*-dropout candidates have not been completed, we do not derive statistical properties of the sample in this paper. In Spring 2005, the SDSS essentially completed its imaging survey in the Northern Galactic Cap, with a total area of $\sim 7550 \text{ deg}^2$. In Spring 2006, we will continue to search for *i*-dropout quasar candidates in the remaining new area, as well as observe additional candidates in the previously studied area that meet the selection criteria because of improved photometric calibrations. Combining current data with these planned observations, we will be able to define a sample of $z > 5.7$ quasars covering the entire SDSS Northern Galactic Cap area, and use it to refine the measurements of the evolution of the luminosity function and emission line properties of the highest redshift quasars.

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REFERENCES

- Abazajian, K., et al. 2003, AJ, 126, 2081
- 2004, AJ, 128, 502
- 2005, AJ, 129, 1755
- Adelman-McCarthy, J., et al. 2005, ApJS, in press (astro-ph/0507711)
- Anderson, S. F., et al. 2001, AJ, 122, 503
- Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
- Becker, R. H. et al. 2001, AJ, 122, 2850
- Chiu, K. et al., 2005, AJ, submitted
- Collinge, M. J., et al. 2005, AJ, 129, 2542
- Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J., 1998, AJ, 115, 1693
- Epps, H.W., & Miller, J.S. 1998, Proc. SPIE, 3355, 48
- Fan, X. et al. 1999, ApJ, 526, L57
- 2000, AJ, 120, 1167
- 2001a, AJ, 121, 31
- 2001b, AJ, 122, 2833 (Paper I)
- 2002, AJ, 123, 1247
- 2003, AJ, 125, 1649 (Paper II)
- 2004, AJ, 128, 515 (Paper III)
- Fukugita, M., Ichikawa, T., Gunn, J.E., Doi, M., Shimasaku, K., & Schneider, D.P. 1996, AJ, 111, 1748
- Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633
- Gunn, J.E., et al. 1998, AJ, 116, 3040
- Gunn, J.E., et al. 2005, AJ, submitted
- Hogg, D., et al. 2001, AJ, 122, 2129

- Ivezić, Ž., et al. 2004, *Astronomische Nachrichten*, 325, 583
- Laurent-Muehleisen, S. A., Kollgaard, R. I., Feigelson, E. D., Brinkmann, W., & Siebert, J. 1999, *ApJ*, 525, 127
- Lupton, R.H., Gunn, J.E., & Szalay, A. 1999, *AJ*, 118, 1406
- Lupton, R. H., Gunn, J. E., Ivezić, Z., Knapp, G. R., Kent, S. M., & Yasuda, N., 2001, ASP Conf. Ser. 238: *Astronomical Data Analysis Software and Systems X*, 10, 269
- Martini, P., Persson, S.E. Murphy, D.C., Birk, C., Shectman, S.A., Gunnels, S.M., & Koch, E. 2004, *Proc. SPIE*, 5492, 1653
- Pier, J. et al. 2003, *AJ*, 125, 1559
- Richards, G. T., et al. 2002a, *AJ*, 123, 2925
- Richards, G. T., Vanden Berk, D. E., Reichard, T. A., Hall, P. B., Schneider, D. P., SubbaRao, M., Thakar, A. R., & York, D. G. 2002b, *AJ*, 124, 1
- Sambruna, R. M., Maraschi, L., & Urry, C. M. 1996, *ApJ*, 463, 444
- Schlegel, D.J, Finkbeiner, D.P., & Davis, M. 1998, *ApJ*, 500, 525
- Schneider, D. P., Schmidt, M., & Gunn, J.E. 1991, *AJ*, 101, 2004
- Schneider, D. P., et al. 2003, *AJ*, 126, 2579
- Skrutskie, M. F., et al., 1997, *The Impact of Large-Scale Near-IR Sky Surveys*, ed. F. Garzón, N. Epchtein, A. Omont, B., Burton, & P. Persei (Dordrecht: Kluwer), 25
- Smith, J., et al. 2002, *AJ*, 123, 2121
- Songaila, A., 2004, *AJ*, 127, 2598
- Spergel, D. N. et al. 2003, *ApJS*, 148, 175
- Stalin, C. S., & Srianand, R. 2005, *MNRAS*, 359, 1022
- Strateva, I.V., Brandt, W.N., Schneider, D.P., Vanden Berk, D.G., & Vignali, C. 2005, *AJ*, 130, 387
- Stoeckle, J. T., Morris, S. L., Gioia, I. M., Maccacaro, T., Schild, R., & Wolter, A. 1990, *ApJ*, 348, 141
- Stoughton, C. et al. 2002, *AJ*, 123, 485
- Tucker, D., et al. 2005, *AJ*, submitted

- Vanden Berk, D. E., et al. 2000, *AJ*, 122, 549
- Urry, C. M., & Padovani, P. 1995, *PASP*, 107, 803
- Voges, W., et al. 1999, *A&A*, 349, 389
- White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, *ApJ*, 475, 479
- White, R. L., et al. 2000, *ApJS*, 126, 133
- White, R. L., Becker, R. H., Fan, X., & Strauss, M. A., 2003, *AJ*, 126, 1
- York, D. G., et al. 2000, *AJ*, 120, 1579

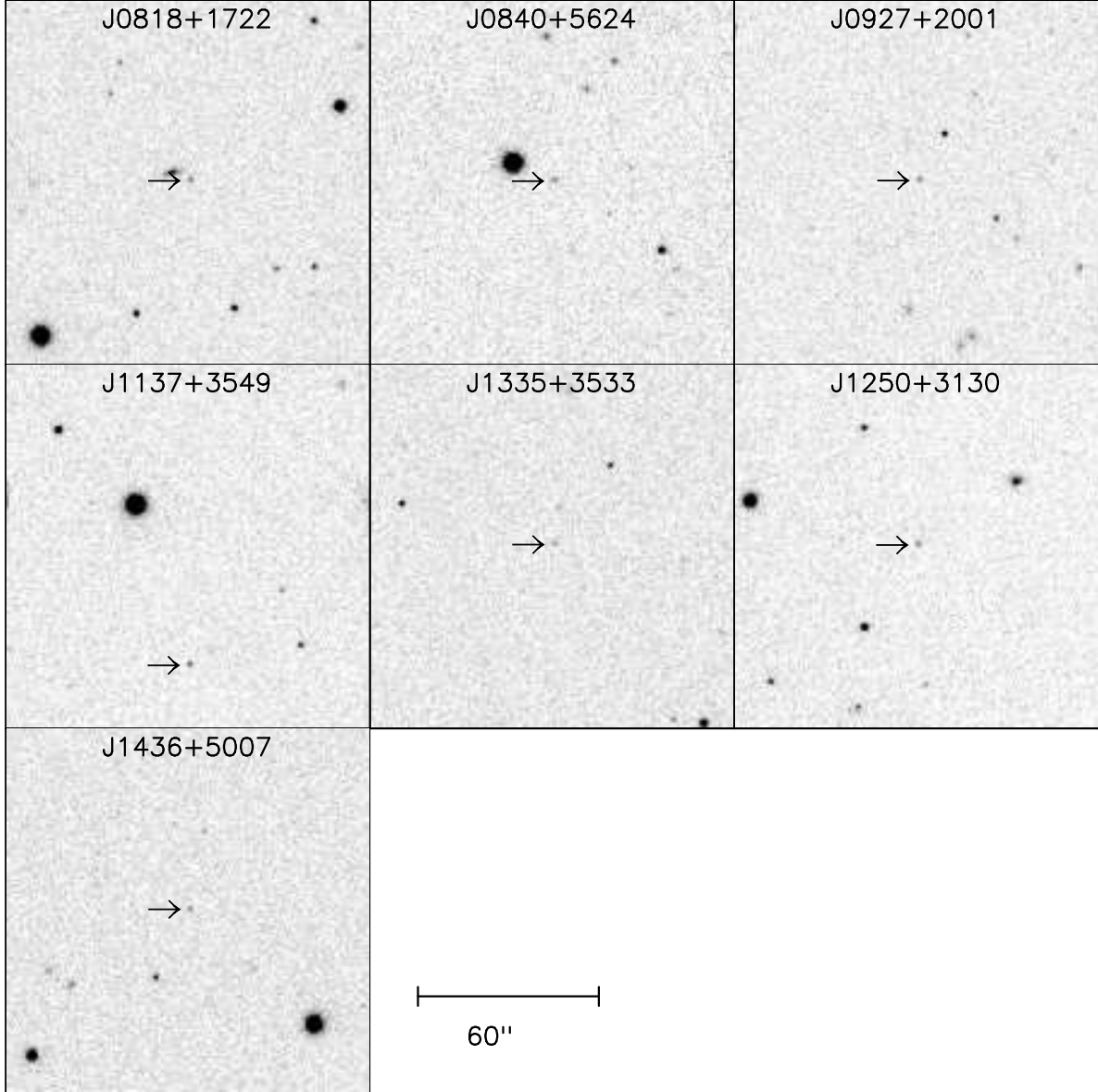


Fig. 1.— SDSS z -band images of the seven new $z > 5.7$ quasars. Each side of the finding chart is 120". North is up and East is left.

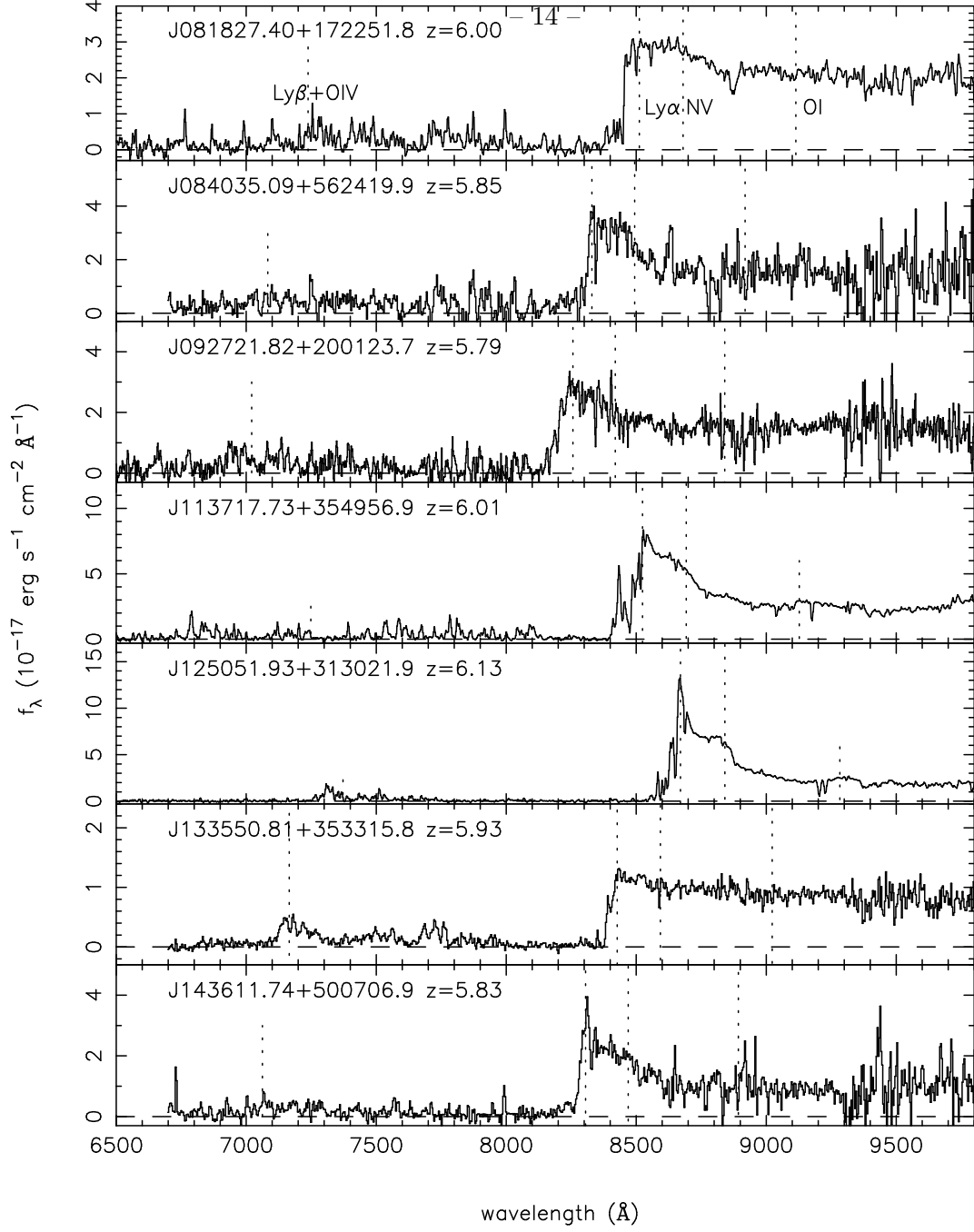


Fig. 2.— Spectra of the seven new quasars at $z > 5.7$. The spectral resolutions are between 500 and 4000, depending on the spectrograph used. Vertical lines indicate wavelengths at which major emission lines are expected.

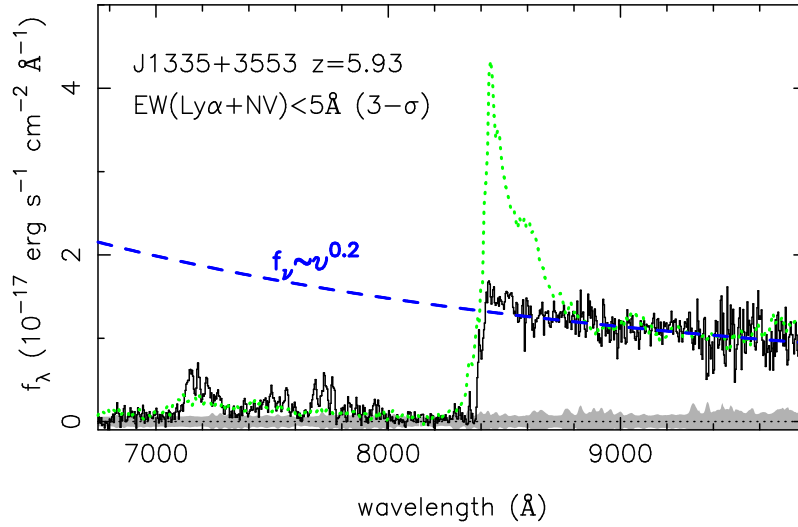


Fig. 3.— Spectrum of the lineless quasar SDSS J1335+3533 ($z = 5.93$). The shaded area around zero flux shows the $1\text{-}\sigma$ error array. The dashed line is the best-fit power law. The absolute value of power-law index is uncertain by ~ 0.3 due to possible error in the spectrophotometric calibration. The dotted line shows the composite spectrum of 16 quasars at $z > 5.7$ (arbitrary normalization). The $\text{Ly}\alpha\text{+NV}$ emission line has an average rest-frame equivalent width of $\sim 70\text{ \AA}$ at $z > 4$, while for SDSS J1335+3533, it has a $3\text{-}\sigma$ upper limit of 5 \AA .

Table 1. Photometric Properties of Seven New $z > 5.7$ Quasars

Quasar (SDSS)	redshift	i	z	J	SDSS run
J081827.40+172251.8	6.00 ± 0.02	22.19 ± 0.22	19.60 ± 0.08	18.54 ± 0.05	5045
J084035.09+562419.9	5.85 ± 0.02	22.43 ± 0.34	19.76 ± 0.10	19.00 ± 0.10	4204
J092721.82+200123.7	5.79 ± 0.02	22.12 ± 0.17	19.88 ± 0.08	19.01 ± 0.10	5138
J113717.73+354956.9	6.01 ± 0.02	22.57 ± 0.30	19.54 ± 0.07	18.41 ± 0.05	4392
J125051.93+313021.9	6.13 ± 0.02	22.14 ± 0.18	19.53 ± 0.08	> 16.5	4623
J133550.81+353315.8	5.93 ± 0.04	22.67 ± 0.99	20.10 ± 0.11	18.97 ± 0.05	4470
J143611.74+500706.9	5.83 ± 0.02	22.76 ± 0.28	20.00 ± 0.12	19.04 ± 0.10	3180

The SDSS photometry (i, z) is reported in terms of *asinh magnitudes* on the AB system. The asinh magnitude system is defined by Lupton, Gunn & Szalay (1999); it becomes a linear scale in flux when the absolute value of the signal-to-noise ratio is less than about 5. In this system, zero flux corresponds to 24.4 and 22.8, in i , and z , respectively. The J magnitude is on a Vega-based system.

Table 2. Continuum Properties of new $z > 6$ Quasars

Quasar (SDSS)	redshift	AB_{1280}	AB_{1450}	M_{1450} (Λ -model)	M_{1450} (Ω -model)	$E(B - V)$ (Galactic)
J081827.40+172251.8	6.00	19.41	19.34	−27.37	−27.14	0.04
J084035.09+562419.9	5.85	20.10	20.04	−26.64	−26.40	0.04
J092721.82+200123.7	5.79	19.94	19.87	−26.78	−26.55	0.03
J113717.73+354956.9	6.01	19.70	19.63	−27.08	−26.85	0.02
J125051.93+313021.9	6.13	19.71	19.64	−27.11	−26.87	0.02
J133550.81+353315.8	5.93	19.96	19.89	−26.81	−26.58	0.01
J143611.74+500706.9	5.83	20.23	20.16	−26.51	−26.28	0.02